Dynamic Control Analysis of Internally Heat Integrated-Top Dividing Wall Column

Liu Jingjing* and Chen Haisheng

***Abstract*—Although The Dividing Wall Column (TDWC) with a top partition is an effective alternative for the separation of ternary mixtures dominated by the lightest component, it can be further intensified by introducing the Internal Heat Integration-The Dividing Wall Column (IHI-TDWC). However, strong internal mass and energy integration complicates the process dynamics and influences the system controllability. In the current work, a kind of decentralized temperature control scheme involving four temperature control loops is developed. The separation of the ternary mixture with methanol, ethanol, and n-propanol is chosen as an illustrative example to evaluate the controllability of the IHI-TDWC through open-loop and closed-loop dynamic process simulation. The results show that the IHI-TDWC keeps good rejection of the throughput and feed composition disturbances.**

***Index Terms*—Dividing wall column, internal heat integration, process control, temperature control**

I. Introduction

Distillation column is a widely used but an energy-intensive unit in the chemical industry [1–4]. In order to enhance its thermodynamic efficiency, many technologies based on energy integration and mass integration were developed. Among these technologies, the Internally Heat-Integrated Distillation Column (IHIDiC) and the Dividing-Wall Column (DWC) are two excellent alternatives [5, 6]. In the IHIDiC, the operating pressure and temperature of the rectifying section are elevated by a compressor, thus the released heat of the rectifying section can be supplied to the stripping section, which should be the heat sink [7]. The IHIDiC can cut down, if not eliminate, the external reboiler and condenser heat duty dramatically. The DWC divides the column into two thermally coupled parts: a pre-fractionator and a main distillation column [8]. The energy consumption of the DWC can be decreased largely as compared with the conventional distillation flowsheets (i.e., the direct and indirect separation sequences).

The DWC has significant temperature difference between the top and bottom, implying a strong irreversibility in the view of second law of thermodynamics. To deal with this problem, introducing internally heat integration technology onto DWC is attempted by several researchers. Suphanit *et al.* proposed a kind of DWC with heat integration between certain positions of the partition, and a certain degree of energy saving can be achieved [9]. Fang et al. pointed out that an intermediate heat exchanger was involved between the pre-fractionator and the main column of DWC to produce thermal coupling effect and reduce the energy consumption of the system [10].

For the separation of ternary mixtures dominated by the lightest component, it is better to locate the partition at the top of the DWC (termed as TDWC). As shown in Fig. 1, the TDWC can be viewed as three linked parts named PRE, SIDE, and STRI. The vapor from the top of the STRI is separated and transferred to the bottom of the PRE and the SIDE, respectively. The liquid from the bottom of the latter two parts flows to the top of the former part. Recently, Ji *et al.* developed a novel configuration combining internally heat integration and DWC, which will be called internal heat integrated-top dividing wall column (IHI-TDWC); however, the dynamics and control of the IHI-TDWC were not studied.

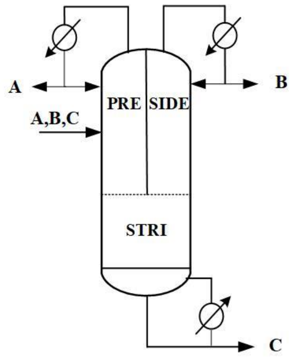

Fig. 1. Schematic of TDWC.

In the current work, a four-point temperature control scheme is developed to examine the controllability of the IHI-TDWC. The separation of a ternary mixture with methanol, ethanol, and n-propanol is taken as an illustrative example to evaluate the open-loop and closed-loop performance of the control scheme. Some concluding remarks are finally summarized in the last section of this article.

II. Steady-state Scheme of IHI-TDWC

Fig. 2 shows the steady-state process design of IHI-TDWC. It is shown that the PRE, STRI, SIDE are set to have equal stage number, i.e., 45 stages, with the feed location at 17th stage of PRE. The feed flow rate is 100 kmol/h, and the boiling points of the methanol, ethanol, and n-propanol are 337.9K, 351.5K, and 368.9K. The feed compositions of the methanol, ethanol, and n-propanol are 50 mol %, 25 mol %, and 25 mol %, respectively, implying that the feed is dominated by the lightest methanol. Table I lists the operating conditions and product specifications of IHI-TDWC. The vapor from the top of the STRI is pressurized with a compressor and then separated and

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The authors are with the College of Information Science and Technology, Beijing University of Chemical Technology, Beijing, China. E-mail: chenhs@mail.buct.edu.cn (C.H.)

*Correspondence: 2020200728@buct.edu.cn (L.J.)

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transferred to the bottom of the PRE and the SIDE. The liquid from the bottom of the latter two parts flows to the top of the former part by two throttle valves. The elevated heat of the upper section of the PRE (i.e., from 2nd stage to 14th stage) and the whole section of the SIDE is transferred to the relative section of the STRI. By implementing internal heat integration, the IHI-TDWC can greatly reduce energy consumption as compared with TDWC.

The internally heat integration is calculated by:

$$Q = UA\Delta T \tag{1}$$

where U (W/m^{2}K) is the total heat transfer coefficient, A (m^2) represents the heat transfer area and ΔT (K) is the temperature difference between pairing stages.

TABLE I: OPERATING CONDITIONS AND PRODUCT SPECIFICATIONS OF THE IHI-TDWC

Parameter		Value
Column pressure (atm)		
PRE		2.2
SIDE		2.2
STRI		1.0
Feed flow rate (kmol/h)		100
Stage pressure drop (atm)		0.0068
Feed composition (mol %)		
Methanol		50
Ethanol		25
N-propanol		25
Product specifications (mol %)		
PRE	Methanol	99
SIDE	Ethanol	99
STRI	N-propanol	99

III. TEMPERATURE CONTROL SYSTEM SYNTHESIS AND DESIGN

As shown in the Fig. 2, there are 11 available manipulated variables involved in the IHI-TDWC, i.e., reflux ratio (R_{PRE} and R_{SIDE}), distillation flow rate (D_{PRE} and D_{SIDE}), condenser heat duty (Q_{PRE} and Q_{SIDE}), bottom effluent flow rate (B_{PRE}, B_{SIDE}, and B_{STRI}), reboiler heat duty (Q_{reb}), and work of compressor (Q_C).

The operating pressures of the PRE and SIDE are controlled by Q_{PRE} and Q_{SIDE}, respectively. The liquid bottom levels of the PRE, SIDE, and STRI are regulated by B_{PRE} , B_{SIDE}, and B_{STRI}, respectively. D_{PRE} and D_{SIDE} are adopted to regulate the level of reflux drum of the PRE and SIDE since their reflux ratios are less than 3. According to the principle of proximity, Q_{reb}, R_{PRE}, and R_{SIDE} are employed to control the temperature of three sensitive stages in the STRI, PRE, and SIDE. Since the compression ratio is the key factor that affect the steady-state performance of the IHI-TDWC separating the lightest methanol dominated mixture and the PRE contains a large amount of energy, it is thus reasonable to use Q_C to control the temperature of a sensitive stage in the PRE [11–12]. Fig. 3 depicts the derived four-point temperature control scheme. It is noted that the control scheme comprises of two temperature control loops in the PRE and two temperature control loops in the STRI and SIDE, respectively.

In the following section, the locations of the four sensitive stages are determined according to the sensitivity analysis and the control scheme will be detailly evaluated [13].

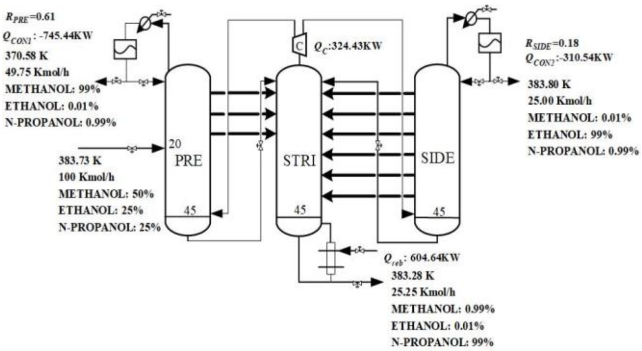

Fig. 2. Process design of IHI-TDWC.

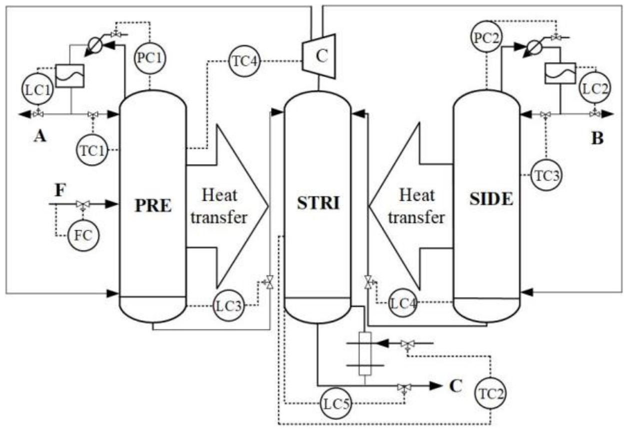

Fig. 3. Temperature control scheme of IHI-TDWC.

IV. SIMULATION RESULTS AND ANALYSIS

A. Sensitivity Analysis

Fig. 4 shows the results of the steady-state gain of the temperatures of all stages in the STRI, PRE, SIDE, and PRE and their corresponding manipulated variables, Q_{reb}, R_{PRE}, R_{SIDE}, and Q_C. It is noted that the temperature of the 31st stage in the STRI, the 29th stage in the PRE, the 2nd stage in the SIDE, and the 34th stage in the PRE should be selected as controlled variables.

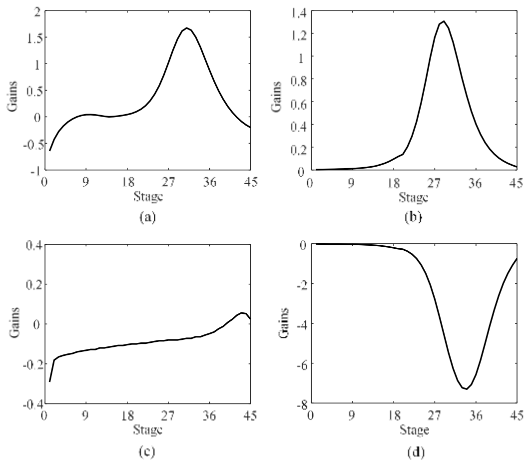

Fig. 4. Sensitivity analysis of IHI-TDWC: (a) Q_{reb}, (b) R_{PRE}, (c) R_{SIDE}, (d) Q_C.

Five liquid level control loops are controlled by proportional controllers (K_C =2) and pressure control loops by PI controllers (K_C=12, T_i=2 min). A 1-min deadtime is assumed for each temperature control loop. All temperature controllers are tuned according to the Tyreus-Luyben rule [13, 14]. The temperature controller parameters are listed in Table II.

TABLE II: TEMPERATURE CONTROLLER PARAMETERS FOR THE DEVELOPED CONTROL SYSTEM

Controller	Manipulated variable	Controlled variable	K_C	T_i (min)
TC1	R_{PRE}	T_{29}	25.8	26.4
TC2	Q_{reb}	T_{31}	17.7	39.6
TC3	R_{SIDE}	T_2	939.3	92.4
TC4	Q_C	T_{34}	3.8	66.0

B. Open-Loop Evaluation

Open-loop responses of the control system are sketched in Fig. 5 in face of ±1% step change in feed flow rate. Throughout the article, the positive responses are represented by solid lines and negative responses by dotted lines. It is noted that all product purities of the IHI-TDWC can transition to a new steady-state value smoothly. The composition of ethanol in the top of the SIDE showed asymmetry and non-minimum phase phenomenon. Fig. 6 displays the open-loop responses of the control system in the face of ± 0.1% step change in the feed composition of methanol. The IHI-TDWC reached a new steady state at around 40h, and the composition of n-propanol in the bottom of the STRI showed asymmetry and non-minimum phase phenomenon.

C. Closed-Loop Evaluation

Fig. 7 describes the closed-loop responses of the control system in face of ±10% step change in feed flow rate. The three product compositions can return to their set-points within 15 hours with acceptable steady-state offsets. In Fig. 8, the closed-loop responses of the control system in face of ±10% step change in the methanol composition are plotted. The control system handles the disturbances of feed composition rapidly and does well in maintaining the three product purities. The results showed that the four-point temperature control scheme is effective and feasible, and the IHI-TDWC is controllable despite of strong nonlinearity.

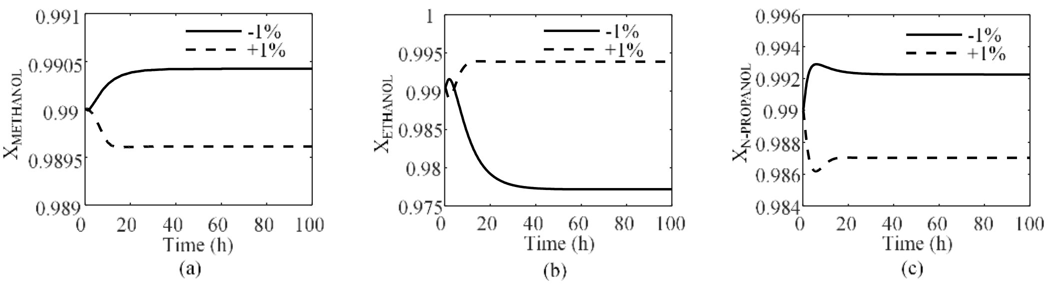

Fig. 5. Open-loop responses in face of ±1% step change in feed flow rate: (a) $x_{methanol}$ in the top of the PRE, (b) $x_{ethanol}$ in the top of the SIDE, (c) $x_{n\text{-}propanol}$ in the bottom of the STRI.

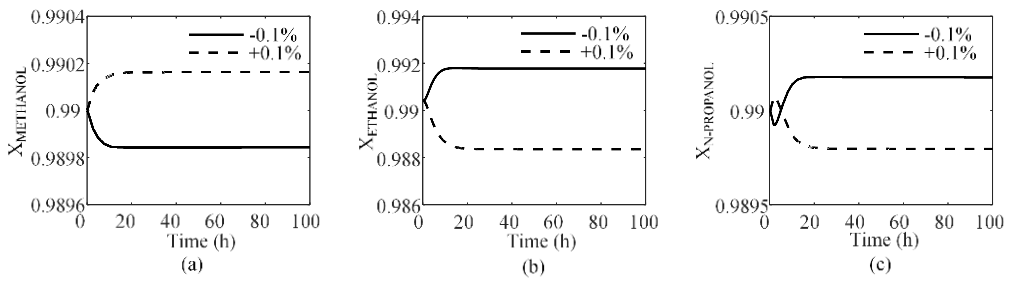

Fig. 6. Open-loop responses in face of ±0.1% step change in feed composition of methanol: (a) $x_{methanol}$ in the top of the PRE, (b) $x_{ethanol}$ in the top of the SIDE, (c) $x_{n\text{-}propanol}$ in the bottom of the STRI.

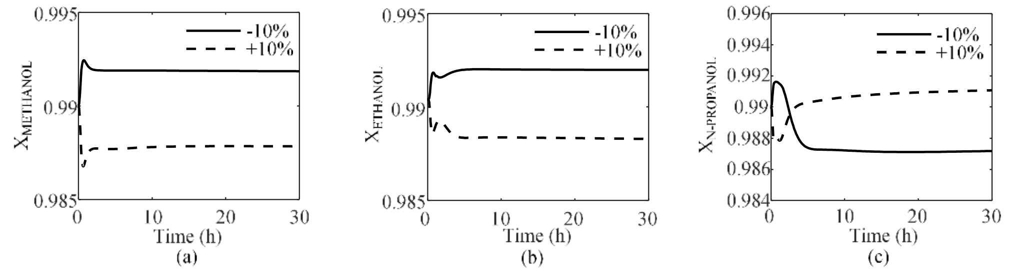

Fig. 7. Closed-loop responses in face of ±10% step change in feed flow rate: (a) $x_{methanol}$ in the top of the PRE, (b) $x_{ethanol}$ in the top of the SIDE, (c) $x_{n\text{-}propanol}$ in the bottom of the STRI.

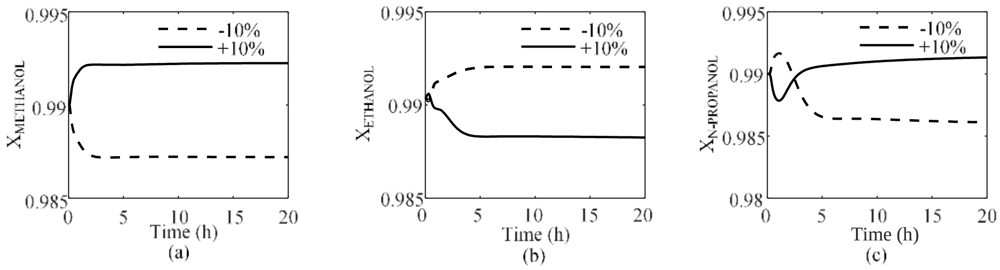

Fig. 8. Closed-loop responses in face of ±10% step change in feed composition of methanol: (a) $x_{methanol}$ in the top of the PRE, (b) $x_{ethanol}$ in the top of the SIDE, (c) $x_{n\text{-}propanol}$ in the bottom of the STRI.

V. Conclusions

A four-point temperature control scheme was developed to evaluate the controllability of the IHI-TDWC in this work. Taking the separation of a ternary mixture with methanol, ethanol, and n-propanol as an illustrative example, the open-loop dynamics of the IHI-TDWC and the closed-loop performance of the developed control scheme are analyzed via process simulation. The results indicated that the IHI-TDWC is feasible and controllable in spite of high nonlinearity.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Liu Jingjing conducted the research and data analysis; Chen Haisheng conducted the research and analyzed the data, all authors had approved the final version.

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